High sound quality and concha headphones: where are the limitations?

Lola Blanchard

Bang&Olufsen ICEpower / DTU, Gl. Lundtoftevej 1b, st., 2800 Lyngby, Denmark
lob@bang-olufsen.dk

Concha headphones (the small type of headphone that rests at the entrance of the ear canal) are the most popular type of headphones for every day use. However, the sound quality produced by even "high quality" concha headphones is rather poor. This paper gives an overview of the different factors that affect the quality of this type of headphones, describes the measurement difficulties, and presents the results of some models. The leakage between the headphone and the ear changes every time the headphone is inserted in the ear. This alters the perceived sound quality, especially at low frequencies, and makes measurements very difficult. Moreover, because of energy efficiency considerations, a typical transducer design is prone to nonlinear behaviour, and a high distortion rate can be measured for most concha headphones. The measured transducer parameters and leakage have been implemented in a model realised in Simulink. The simulation model, which makes it possible to study the influence of the various parameters including the uncontrolled leakage, is the first step towards developing a compensation technique.

1   Introduction

Nowadays more and more people own a set of headphones to accompany a mobile phone, a mp3 player, or any portable device that requires reproduction of sound. The most common type of headset that is provided with such electronic devices are concha headphones; See Fig.1. They are small enough to be placed in the external ear and rest on the pinna. Usually, the headset provided

Figure 1: Ipod´s concha headphone. One of the most sold concha headphones on the current market

with a device is of poor quality as the main emphasis has been placed on the device itself and not on the accessories. Moreover, the fact that the headphone rests on the pinna and is not perfectly sealed to the ear implies that sound is lost through that leak, especially at low frequencies. A common tendency is to raise the volume to get more bass. However, increasing the level will increase the distortion.

There are other types of headphones without the same disadvantages. Therefore, they tend to be more appreciated for their sound quality. Circum aural headphones, which enclose the full ear, are perfectly sealed to the ear. They have a larger transducer, and are less subject to nonlinear phenomena. However, due to their larger size, they are not as practical as concha headphones. Another type of headphone is the intra aural or in-ear headphones that are inserted completely inside the ear canal. This way, there is no leak to the outside. As they are radiating in such a small cavity a large displacement of the membrane is not required to achieve a high sound pressure level even at low frequencies, and therefore the nonlinear distortion is lowered. Being very small, they are very handy. However, closing completely the ear canal can be very uncomfortable, a feeling of over pressure can occur. The bass frequencies can also be exaggerated and become unpleasant. The occlusion effect

can happen, where the listener hears booming sounds of its own voice.

For all these reasons it has been decided to study concha headphones and try to develop their design in order to achieve a better sound quality. To do so, a study of the major limiting parameters that are altering the sound quality has been carried out. First, the coupling to the ear canal is studied and then the transducer's properties. In addition to the poor performance of this type of headphones, there are some measurement issues, and they will also be discussed in this paper. Finally, some models of concha headphones will be presented as they are the first step towards improving their sound quality.

In this paper, the Bang & Olufsen A8 headphone have been chosen to illustrate the phenomena that are mentioned.

2   Coupling ear and earphone

One of the main drawbacks of concha headphone is the seal to the ear canal. From one individual to the other, and even from one placement to another, the seal to the ear is not the same as the headphone cannot be placed in the exact same way. If the seal was perfectly air tight, then the frequency response would be flat until the resonance frequency and then drop by 12dB per decade (in the case of a single degree of freedom system) [1] .

It is very easy to reach high levels at low frequency when radiating into a small volume. If the seal is not air tight, the assumption that the headphone radiates into a volume does not hold anymore, and it becomes more difficult to generate low frequencies. The larger the leakage, the less bass is present. The frequency response of Bang & Olufsen A8 headphones is presented with different sizes of leakage in Fig.2.

3   Properties of the transducer

The transducer used in concha headphones is a typical electrodynamical microtransducer. It is designed in order to have a good sensitivity and very low power consumption. Therefore, the moving mass is kept very low. In order to keep the costs down, the suspension and diaphragm are made in the same piece of thin plastic.
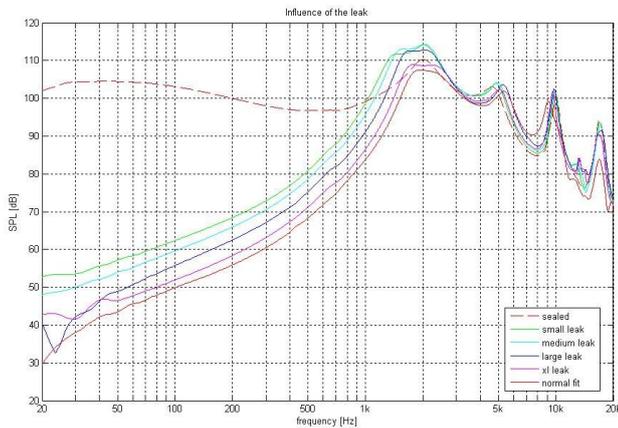
Figure 2: Non linear Bl factor. The measurement has been performed on the B&O A8 concha headphones, with a closed back volume and for different sizes of leak (see section 4.3.2) in a B&K 711 coupler

Usually, for an electrodynamical transducer, the main causes of nonlinear distortion is the fact that the force factor, the inductance of the coil, and the compliance of the suspension depend on displacement [2]. Their dependence in time and temperature is also of relevance; however, this is not treated in this paper. For microspeakers, the influence of the inductance of the voice coil is very small and starts to play a role only at very high frequencies. Therefore, the contribution to the nonlinear behaviour can be neglected.

All in all, the major limitations in the good sound reproduction for such transducers are the nonlinear force factor, and especially the suspension´s compliance.

3.1 Force factor

The force factor of a loudspeaker is the integral of the magnetic flux B and the effective length of the coil, l, that is in the flux,

$$Bl(x) = \frac{l}{h} \int_{x-h/2}^{x+h/2} B(u)du, \qquad (1)$$

where h is the magnet gap.

The force factor depends on the excursion. If the coil moves outward, there will be less windings in the magnet gap and the force will decrease. If the coil goes away from the rest position, the force factor drops. The configuration of the voice coil is usually overhung, which means that the length of the voice coil is larger than the length of the pole piece. This is due to the fact that the diaphragm is directly bounded to the coil, and it should not touch the pole piece while moving inward. In this case, the same number of windings is in the magnetic flux for displacements smaller than $x_{max} = (h - h_g)/2$ (See Fig.3). Therefore the force factor is constant in that range and decreases with the excursion. Depending on the magnetic flux, and the material properties of the suspension, the force factor can be symmetric, which would be the second best case after the linear force factor, or asymmetric.
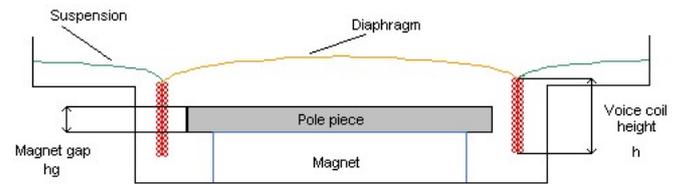

Figure 3: Transducer at rest position. The diaphragm is bounded to the coil, which is longer than the magnet gap (overhung)

The force factor of the Bang & Olufsen A8 has been measured with a Klippel analyser (see section 4.1) and is displayed in Fig.4. Any variation in the force fac-
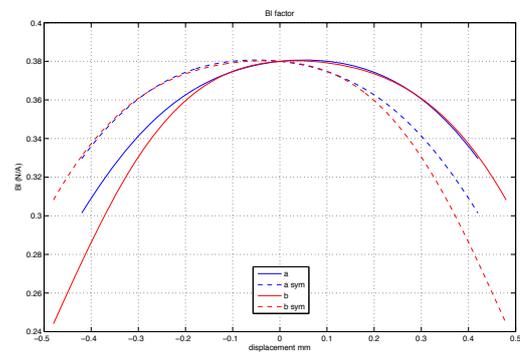

Figure 4: Nonlinear Bl factor. The measurement has been performed on the B&O A8 concha headphones, at two different levels

tor will affect the coupling between the mechanical and electrical part since the force f is related to the current i through

$$f = Bl \cdot i. \qquad (2)$$

Having an asymmetric force factor will introduce a DC offset in the rest position of the membrane. As the force factor is different when the diaphragm moves inward or outward, it will not push the membrane with the same strength, thus creating a disequilibrium and the resting position of the diaphragm will be shifted.

3.2 Compliance of the suspension

The suspension of the transducer is made of a very thin plastic material. The suspension works as a spring which is pushing the diaphragm back to the rest position. At low excursions, the suspension acts as linear spring but when the displacement is increased, its force is stronger than the force generated by a linear spring would be [2]. Therefore, the compliance of the suspension changes with the displacement. At the rest position, it is soft and the compliance is at maximum. The more the displacement increases, the more streched the suspension is. It becomes harder and harder to stretch it, the spring constant becomes higher and higher, and therefore the compliance decreases. The compliance can be symmetric or not depending on whether the suspension stretches in

the same way while moving inward or outward. As seen in Fig.5, it is very asymmetric for the B&O A8. The slight change of pattern with the level can be due to measurement errors. The softest part of the suspension is not at the zero position. If the suspension is nonlinear, when playing an AC voltage, the position of the membrane will tend to the softest part of the suspension and a DC shift will be generated.
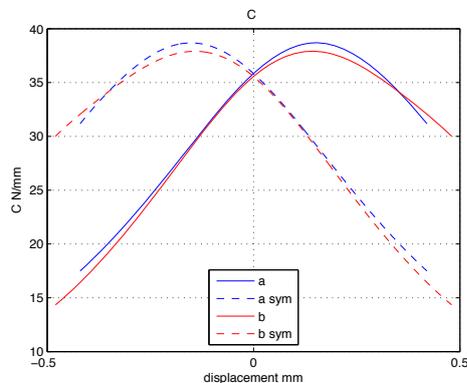

Figure 5: Nonlinear compliance of the suspension. The measurement has been performed on the B&O A8 concha headphones, at two different levels

3.3 Distortion

The nonlinear parameters of the transducer will give raise to distortion, since the movement of the membrane is not properly following the pattern it ideally should. As seen in Fig.6, the total harmonic distortion is high at low frequencies, for large displacements, and drops at high frequencies. Notice that if the headphone is completely sealed to the ear, the displacement is extremely small and therefore the distortion is very low. The peak at around 8.7 kHz is due to the resonance of the ear.
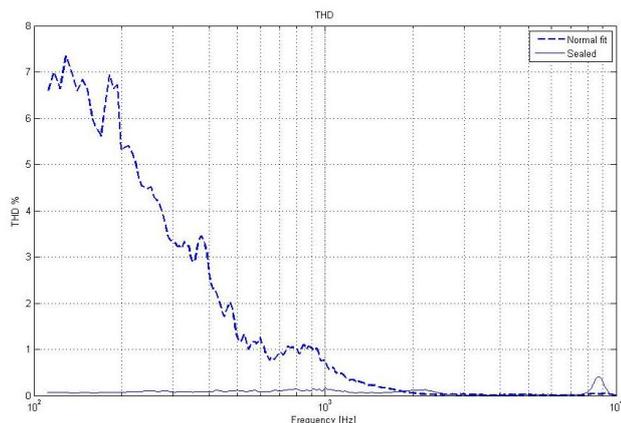

Figure 6: Total harmonic distortion of the B&O A8 concha headphones playing in the 711 coupler

4 Measurement difficulties

4.1 Microtransducers

The Klippel analyser is a distortion analyser that can be used, among other things, to determine the linear and nonlinear parameters of a speaker. The analyser sends a signal through an amplifier to the transducer and to an identification system. The current at the terminal of the transducer is measured and compared in real time to the intensity at the output of the identification system, which is fitting the parameters to the model. In order to determine all the parameters, an impedance measurement is performed. However, as the mechanical parameters are mixed together with the force factor, a laser displacement measurement is carried out.

In order to get a proper signal for the laser measurement, a dot of white ink should be put on the diaphragm, the latter being transparent. The dot should be small enough not to add some mass to the diaphragm. The average weight of the dot has been found to be 0.1mg. Since the accuracy of the measured moving mass is 0.5mg, the mass of ink can be neglected.

The question of where to place the dot is also relevant. In the middle, the diaphragm is more subject to break ups, and the dot is adding some strength to the membrane, therefore the movement of the diaphragm can be disturbed by it.

4.2 Vented box

Since concha headphones transducer are usually of poor performances, their back volume design is very important. It is used to compensate for the transducers behaviour, mainly add some bass and sometimes cancel out the resonance of the transducer depending on its frequency. It is almost always a vented box in order to increase the bass response.There can also be some slits or holes in order to shape its frequency response. This means that the headphone has several resonances, the transducer's resonance and the resonances between vent and slits.

The back volume is very small, typically around 300 mm^3, and vent and slits are also of very small dimensions. Often the vent is curved or the windings cavity is also used as a vent etc. This makes geometric measurements very difficult to carry out. Since the headphone is a system with several resonances, it is not possible to obtain proper measurements of the transducer parameters with the Klippel analyser. There are therefore some uncertainties that can lead to wrong modelling.

4.3 Measurements in the ear

The headphones are designed to be used in the ear. Therefore their frequency response in free air does not tell much about the sound quality. It must be measured in the ear.

4.3.1 Real ear measurements

The main difficulty is that every individual has different size and shape of ears; therefore the response of the headphone is different for every user. Moreover, eardrum frequency response measurements are very difficult to carry out. Another drawback is that obviously, laser measurements cannot be performed in the ear so

the transducer parameters cannot be obtained this way.

To simplify the measurements, a dummy head can be used. This does not solve the problem of the differences between human ears, but it makes it possible to measure the frequency response at the tympanic membrane.

4.3.2 Leak measurements

In order to have repeatable measurements of the leak between the headphone and the ear, a controlled leak device has been constructed. It makes it possible to reproduce the desired amount of leak by varying the opening to the outside in a precise way.

Another measurement has been carried out in order to measure the leak; see Fig.7. A loudspeaker is placed in front of the dummy head and a headphone is placed in one ear. The frequency response of both ears is measured and compared. The amount of sound that goes in the ear where the headphone is, is assumed to be the amount of sound that would be lost through the leak if the headphone was playing, at least for low frequencies [3]. In order to take into account only the leak between the ear and the headphone, the back volume has been completely sealed.

Figure 7: Measurement of the leak. The loudspeaker is placed at 1m in front of the dummy head. On one ear is the headphone, while the other one is left free

4.3.3 Radiation impedance

In order to have an accurate model, the radiation impedance should be measured. The radiation impedance of the leak between the ear and the headphone has to be measured, as well as the radiation impedance of all the openings of the ear canal to the outside. Since all these openings are very small, it is difficult to mechanically measure the dimensions that are needed to calculate the radiation impedance.

5 Models

5.1 Transducer model

A Simulink model has been designed in order to investigate the influence of the nonlinear parameters. It has been possible to predict the Total Harmonic Distortion for the raw transducer radiating in free air (See Fig.8). The displacement is very small when the headphone is placed in the ear, the maximum THD is about 0.4%. The model was underestimating the THD in this configuration, therefore no prediction could be obtained.

It has been chosen to use a power series expansion to model the force factor and the suspension´s compliance, since the Klippel analyser is using them. It is accurate in a certain range of displacement, depending on its order. However, outsied the excursion range, the polynomials diverge very fast. It is difficult to measure in the full excursion range of the microspeaker, therefore, at extreme displacements, the polynomials might not be the best approximation. It has been shown that Gaussian functions fit better for the force factor and the compliance of the suspension as they tend to a stable value when the excursion range is increased [4].
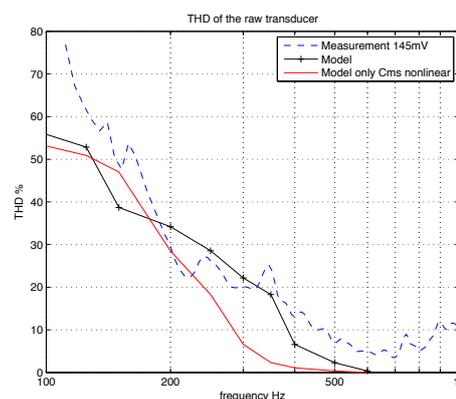

Figure 8: Predicted THD for the B&O A8 radiating in free air with a power input of 1mW. In the model, the force factor is considered as linear first and then nonlinear

5.2 Effect of the leakage

Several models have been used in order to see the effect of the leakage on the headphone. They are all realised in Pspice, and the nonlinearities of the transducer have not been included. The leak has been modelled as suggested in [3], see Fig.9. The parameters R and C corresponds to the damping of the skin when the headphone is vibrating, and L corresponds to its mass.
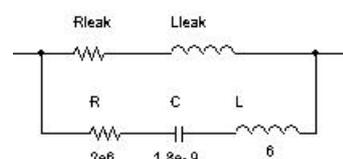

Figure 9: Model of the leak from [3].

At first, a model corresponding to the setup with a loudspeaker in front has been developed. Since in this setup the headphone is not playing, the vibration is not relevant so only the first branch of the leak (R_{leak} and L_{leak}) is included in the model. The divergence between the model and the measurement is probably due to the estimation of the radiation impedances. The headphone is also vibrating because of the excitation from the loudspeaker, and this has not been included. At high frequencies it comes from the fact that the 711 coupler
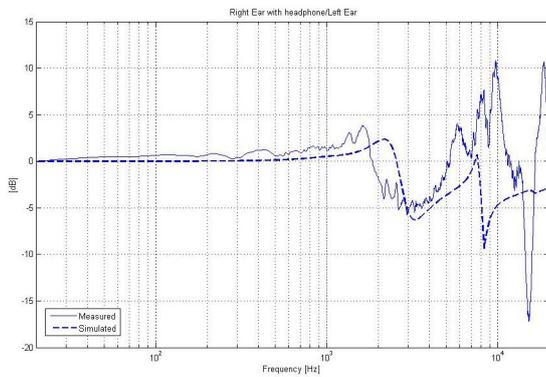
Figure 10: Influence of the leak. Transfer function between the ear with headphone and the other ear

model provided by B&K is accurate only up to 5kHz, and also because the reciprocity assumption on which is based the set up might not hold any longer.

Once the leak parameters R_{leak} and L_{leak} have been determined, they have been implemented in a headphone model of the B&O A8 playing in the B&K 711 coupler, from [5].
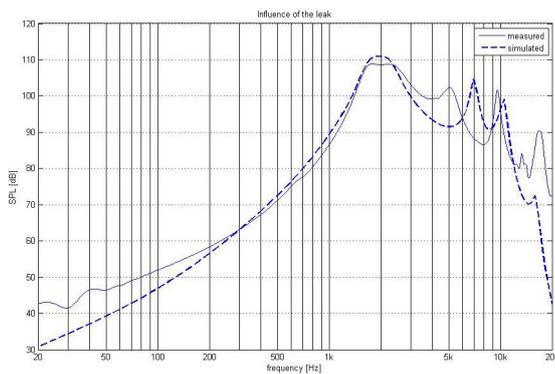

Figure 11: Simulation and measurement of the frequency response of the B&O A8 playing in the 711 coupler

The discrepancy between the simulation and the measurement at high frequency is due to the model of the 711 coupler, and also to the headphone model for which the different parameters have been difficult to measure. At low frequencies, the noise floor of the room could not be avoided when the measurement was carried out.

6 Conclusions

A non exhaustive list of the drawbacks of concha headphones has been presented. They are mainly of two kinds: the transducer properties and the coupling between the ear and the headphone.

Concha headphones are mostly used with battery powered devices, therefore they cannot draw too much power, otherwise the battery will not last long enough. Therefore, the moving parts must be very light; the diaphragm and suspension are made of very thin plastic material. This is the reason why the suspension is usually very

nonlinear in this type of headphone.

Due to their size and to production cost, it is not possible to use a large or heavy magnet, and the magnetic flux is not uniform, and this introduces some more non-linearities and leads to distortion.

When designing headphones, it should be kept in mind that the environment in which they are playing, say the ear of the listener, is different for each user, and this makes it difficult to achieve a good sound quality that will suit every person. When coming to modelling, the parameters need to be measured, and this can easily be inaccurate, and an artificial ear is used. Measurements in a dummy head are not sufficient to conclude on the headphone´s quality. Real ear measurements should be carried out to see the range of variation of the response of the transducer in a panel of listeners.

Acknowledgments

References

[1] J. Borwick, "Loudspeaker and headphone handbook", third edition, (2001)

[2] W. Klippel, "Loudspeaker nonlinearities - Causes, Parameters, Symptoms".

[3] M. Tikander, "Modeling the attenuation of a loosely-fit insert headphone for augmented reality audio", *AES 30th international conference*, (2007)

[4] F. Agerkvist, "Modelling Loudspeaker Non-Linearities", *AES 32th international conference*, (2007)

[5] A.R. Hansen, "Modelling and optimisation of headphones", Master of Science thesis, (2007)